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PERFORMANCE EVALUATION AND MYTHS REGARDING RADON ANALYSIS VIA E-PERMS: ACTUAL FIELD TEST DATA

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ABSTRACT

This paper reports field results of E-PERMs in both the S-Chamber and their keeper caps. The results have been compiled during the past two years covering over 5,000 measurements. Data has been grouped to show precision (co-located tests), accuracy (radon chamber results), and electret stability. The latter results were also broken down into S-Chamber versus keeper cap versus electret series. Besides the aforementioned, a major emphasis will be comparing on-site E-PERM data versus those E-PERMs mailed overnight throughout the country. Overall the data showed that the E-PERMs are accurate and very precise. However, with regard to electret stability, older series and physically older electrets within a series appear to be somewhat more stable or less sensitive than newer electrets. Nevertheless, there is no difference when comparing the results of E-PERMs measured on site versus those air mailed back and forth to the same analysis lab for measurement.

INTRODUCTION

Electret Passive Environmental Radon Monitors* (E-PERM®s) are widely used for measuring ^{222}Rn in air. They, and the electret ion chamber (EIC) technology they are based on, have been described fully in earlier publications (Kotrappa et al. 1988, 1990, 1992). The EIC contains a charged electret (an electrostatically-charged disk of Teflon®) which collects ions formed in the chamber by radiation emitted from radon and radon daughter products. When the device is exposed, radon diffuses into the chamber through filtered openings (EPA 1992 Device Protocols). As the ions are formed inside the chamber, they are drawn to the electret and reduce its surface voltage. The voltage reduction is directly proportional to the radon concentration and the electret exposure time.

Quality E-PERMs should exhibit very little voltage loss [1 volt per week] due to internal electrical instabilities (EPA 1992 Device Protocols, Rad Elec E-PERM System Manual 1991). In addition, co-located detectors should readily meet EPA's coefficient of variation (COV), a measure of electret precision, of less than or equal to 10 % at 4 pCi/L or greater (Rad Elec System Manual 1991). The purpose of this paper is to confirm these claims with field data. Further, this paper will investigate claims that certain series of electrets are more stable than others and that electrets are affected by air transport.

MATERIALS AND METHODS

E-PERM Radon Monitors

The short-term electrets employed in this work were manufactured by Rad Elec, Inc., encompassing all the series from "SA" to "SJ", with voltage ranges between 750 and 200 volts. The electrets were either stored in keeper caps or S-Chambers also manufactured by Rad Elec or its suppliers.

All of the electrets used in this work were measured at the same lab location, at room temperature and using the same Rad Elec surface potential electret reader (SPER-1). The SPER-1 was checked once a week with two sets of two reference electrets. Additionally, 85% of the measurements were made by one person and 15% by another; frequent cross-checks were made to assure that both persons would obtain the same reading with the same electret.

* E-PERM® is a registered trademark of the product patented and manufactured by Rad Elec Inc., Richmond, VA 23237

In the data obtained below, electrets were grouped by series as well as by green label, those with either an SA, SB, SC, or SD in their serial number prefix, and blue label, those with a prefix in their serial number between SE and SJ. The reason for the green and blue separation is the change in electret manufacturing process and calibration equation calculation (Rad Elec Technical Update Memo #30, 1991).

Radon Sources

Co-located detectors were randomly exposed in homes across the U.S. in every state except Rhode Island, Connecticut, and Delaware. Known levels of radon were obtained from radon chambers at EPA (Montgomery, AL and Las Vegas, NV), Chem-Nuclear Geotech (Grand Junction, CO), and Radon Detection Systems (Boulder, CO).

Precision Determination Procedures

Precision of the electrets in S-chambers (referred to generically as E-PERMs) were determined by exposing two or more E-PERMs side-by-side (no more than four inches away from each other) at a test site; known as duplicate check. These test sites were chosen at random in an attempt to place 50 duplicate E-PERMs each month, per EPA protocol (EPA Device Protocols 1992). Test duration for the duplicate checks was usually two to four days. Each test site was presumed to follow "closed-house conditions" during and 12 hours prior to the test.

The duplicate checks, with average detector results above 2.0 pCi/L, were compared viz. percent coefficient of variation (COV). These results were split into two groups, those with average results between 2.0 and 3.9 pCi/L, and those with average results at or above 4.0 pCi/L. Besides showing the total of these two groups, they were also broken into green and blue electrets groups. (Note, that there were some duplicate sets that used both a green and blue electret.)

Accuracy Determination Procedures

E-PERM accuracy was observed by exposure to known levels of radon in calibration chambers. Results were obtained from calibration checks and from the EPA Radon Measurement Proficiency (RMP) Program. The measurements made were compared viz. individual relative error (IRE) and were split into three groups; overall, green, and blue.

Stability Determination Procedures

Data for stability of electrets was gathered from three different sources. In each case, the voltage change was divided by the time between measurement (in weeks) to get an average volt change per week for each electret. In an attempt to rule out SPER-1 voltmeter errors, which is plus or minus one volt for any given reading (Rad Elec System Manual 1991), only time periods of 14 days or longer were considered. For shorter time periods, i.e. one week, one would not be able to tell if a one volt change was due to the voltage electret loss or due to a voltmeter error.

The first group of stability electrets were monitored while kept in their keeper caps. These electrets were usually newly purchased from Rad Elec and were monitored in an initial stability check before being released into the field for use. The data obtained was broken down by color and series and was compared by average voltage change per week, as were the other two stability groupings.

The second group were electrets stored inside S-chambers that were returned from the field to the analysis lab unused (blanks). E-PERMs from the analysis lab are sent out to the field with an expiration date of one month from the last voltage measurement. If they are not used within the one month's time, they are returned to the analysis lab as unused and re-measured for voltage loss.

The final group of electrets were stored inside S-chambers and monitored at the analysis lab (laboratory blanks). These E-PERMs were either chosen at random or E-PERMs that had performed about 10 or 12 tests without a stability check.

RESULTS

Data in the tables below were carried out to two significant figures. For small sample sizes, less than 30, confidence intervals (CI) were determined using the t-distribution, otherwise the Z-distribution was used.

Precision

Results of the duplication checks are shown in Tables 1 and 2. Column 1 gives the electret grouping. Columns 2 and 3 respectively give the number of electrets in the grouping and the average percent COV. Columns 4, 5 and 6 respectively give the percent COV's sample standard deviation, median value, and maximum value. Finally, column 7 shows a 95% confidence interval of the average. (Note that the "Green" and "Blue" rows will not add up to the "All" row because some duplicate sets used both a green and blue electret.)

Table 1: Percent COV of duplicate check electrets, in S-chambers, with average radon levels between 2.0 and 4.0 pCi/L.

Elec.	No. of	Percent COV				
Group	Elec.	Avg.	Stnd. Dev.	Median	Max.	95% C.I.
Green	5	12	8.1	8.8	25	[2.4, 21]
Blue	68	11	13	5.7	71	[8.2, 14]
All	110	11	12	7.5	71	[8.5, 13]

Table 2: Percent COV of duplicate check electrets, in S-chambers, with average radon levels 4.0 pCi/L and above.

Elec.	No. of	Percent COV				
Group	Elec.	Avg.	Stnd. Dev.	Median	Max.	95% C.I.
Green	12	5.1	4.9	3.8	20	[2.1, 8.2]
Blue	95	5.6	9.1	3.2	76	[3.8, 7.4]
All	141	5.5	7.9	3.3	76	[4.2, 6.8]

Accuracy

Results from the chamber tests are shown in Table 3. Column 1 gives the electret grouping. Respectively, columns 2 and 3 give the number of electrets in the grouping and the average IRE. Columns 4, 5 and 6 give the IRE's sample standard deviation, median value, and the positive and negative maximum value respectively. Finally, column 7 shows a 95% confidence interval of the average.

Table 3: The IRE of chamber exposed electrets in S-chambers.

Elec.	No. of	IRE				
Group	Elec.	Avg.	Stnd. Dev.	Median	Max.	95% C.I.
Green	25	-4.5	15	-8.0	45, -21	[1.7, -11]
Blue	96	-2.2	12	-2.5	54, -25	[0.3, -4.6]
All	121	-2.6	13	-5.0	54, -25	[-0.3, -4.9]

Stability

Results of the three groupings of stability checks are shown in Tables 4 through 8. For Tables 4, 5 and 6, column 1 gives the electret grouping; electret series (prefix of serial number), green, blue, and all. Columns 2 and 3 respectively give the number of electrets in the grouping and the average length of days between measurements. Columns 4, 5, 6, 7 and 8 respectively give the average voltage change per week and the average voltage change's sample standard deviation, median value, 90th percentile value, and 95% confidence interval.

Table 4: Average voltage loss per week of electrets stored in their keeper caps and monitored in the analysis laboratory.

Elec. Group	# of Elec.	Exp. Day	Avg. Voltage Change per Week Avg.	Stnd.Dev.	Median	90th	95% C.I.
A	19	30	0.29	0.25	0.29	0.65	[0.17, 0.41]
B	56	33	0.38	0.40	0.31	0.93	[0.28, 0.48]
C	43	26	0.33	0.34	0.30	0.82	[0.23, 0.43]
D	3	22	0.16	0.22	0.00	0.47	[0.00, 0.56]
E	61	25	0.57	0.41	0.50	1.0	[0.47, 0.67]
F	55	32	0.47	0.38	0.38	1.0	[0.37, 0.57]
G	27	27	0.49	0.37	0.40	0.91	[0.34, 0.64]
H	40	40	0.42	0.52	0.26	0.93	[0.26, 0.58]
I	58	43	0.27	0.23	0.25	0.51	[0.21, 0.33]
J	55	79	0.28	0.16	0.27	0.42	[0.24, 0.32]
Green	121	30	0.34	0.36	0.29	0.76	[0.28, 0.40]
Blue	296	52	0.41	0.37	0.33	0.91	[0.37, 0.45]
All	417	45	0.39	0.37	0.33	0.88	[0.35, 0.43]

Table 5: Average voltage loss per week of electrets stored in S-chambers and returned from the field unused (field blanks).

Elec. Group	# of Elec.	Exp. Day	Avg. Voltage Change per Week Avg.	Stnd.Dev.	Median	90th	95% C.I.
A	34	74	0.10	0.11	0.06	0.24	[0.06, 0.14]
B	439	81	0.22	0.35	0.14	0.47	[0.19, 0.25]
C	189	94	0.16	0.16	0.14	0.36	[0.14, 0.18]
D	10	74	0.09	0.09	0.00	0.19	[0.03, 0.15]
E	250	95	0.22	0.23	0.16	0.50	[0.19, 0.25]
F	925	82	0.22	0.29	0.15	0.50	[0.20, 0.24]
G	73	73	0.41	0.37	0.24	0.86	[0.33, 0.49]
H	98	69	0.28	0.38	0.16	0.58	[0.20, 0.36]
I	242	68	0.41	0.51	0.24	0.96	[0.35, 0.47]
J	125	53	0.85	1.1	0.42	2.2	[0.66, 1.0]
Green	672	84	0.20	0.31	0.14	0.40	[0.18, 0.22]
Blue	1713	79	0.30	0.47	0.18	0.65	[0.28, 0.32]
All	2385	80	0.27	0.43	0.17	0.85	[0.25, 0.29]

Table 6: Average voltage loss per week of electrets stored in S-chambers and monitored at the analysis laboratory (lab. blanks).

Elec. Group	# of Elec.	Exp. Day	Avg. Voltage Change per Week Avg.	Stnd.Dev.	Median	90th	95% C.I.
A	35	20	0.18	0.22	0.00	0.50	[0.11, 0.25]
B	132	20	0.43	0.56	0.32	0.95	[0.33, 0.53]
C	44	19	0.32	0.37	0.23	0.88	[0.21, 0.43]
D	4	18	0.13	0.22	0.00	0.50	[0.00, 0.41]
E	77	19	0.33	0.36	0.30	0.82	[0.25, 0.41]
F	274	21	0.42	0.50	0.33	1.0	[0.36, 0.48]
G	53	21	0.59	0.61	0.44	1.5	[0.43, 0.75]
H	60	23	0.61	0.73	0.36	1.3	[0.43, 0.79]
I	128	31	0.67	0.79	0.44	1.8	[0.53, 0.81]
J	64	29	0.80	1.1	0.50	1.9	[0.54, 1.1]
Green	215	19	0.36	0.49	0.29	0.93	[0.29, 0.43]
Blue	656	24	0.53	0.67	0.38	1.2	[0.48, 0.58]
All	871	23	0.49	0.64	0.35	1.0	[0.45, 0.53]

Tables 7 and 8 show the average voltage change for various voltage ranges for the green and blue electrets from the returned and laboratory blank groups. Column 1 shows the various voltage ranges. Columns 2 and 3 respectively give the number of electrets in the voltage range groupings and the average voltage change per week. Columns 4, 5 and 6 respectively give the average voltage change's sample standard deviation, median value, and 95% confidence interval of the average.

Table 7: Average voltage loss per week of electrets stored in S-chambers for various voltage levels, returned from field unused.

	Green Electrets				Blue Electrets			
Voltage Range	No.of Elec.	Avg.	Stnd. Dev.	Med.	No.of Elec.	Avg.	Stnd. Dev.	Med.
200-299	154	0.14	0.25	0.11	175	0.13	0.13	0.11
300-399	187	0.18	0.27	0.14	247	0.21	0.29	0.15
400-499	151	0.17	0.21	0.15	349	0.22	0.24	0.17
500-599	137	0.26	0.40	0.15	430	0.31	0.45	0.18
600-699	41	0.38	0.52	0.20	380	0.35	0.41	0.22
700+	2	0.24	0.24	0.24	132	0.76	1.0	0.36

Table 8: Average voltage loss per week of electrets stored in S-chambers for various voltage levels, monitored in analysis lab.

	Green Electrets				Blue Electrets			
Voltage Range	No.of Elec.	Avg.	Stnd. Dev.	Med.	No.of Elec.	Avg.	Stnd. Dev.	Med.
200-299	61	0.23	0.29	0.10	56	0.19	0.28	0.14
300-399	62	0.29	0.29	0.29	78	0.28	0.35	0.24
400-499	44	0.45	0.59	0.29	118	0.43	0.50	0.41
500-599	39	0.51	0.58	0.35	169	0.59	0.67	0.44
600-699	9	0.63	0.99	0.44	155	0.70	0.79	0.50
700+	-	-	-	-	80	0.70	0.86	0.47

DISCUSSION

Precision

As one would expect, electrets in S-chambers showed more precision at radon levels at or above 4.0 pCi/L than between 2.0 and 4.0 pCi/L. In either case, the average percent COV calculated in Tables 1 and 2 is nearly half the suggested "in control" level COVs from EPA, 10% and 18% respectively (EPA Home Protocols 1993). The tables also show that E-PERMs have good precision in that the COV levels are skewed to the lower COV values since the group medians are around 70% of the average values. Though the green electrets appear to be somewhat more precise than the blue electrets, there is not enough data to show this, hence the much larger confidence intervals for green electrets.

Accuracy

Table 3 shows the tendency of E-PERMs to slightly under-report results. However this under-reporting is within the 6% to 10% error associated with the overall E-PERM system (Rad Elec System Manual 1991) and well within the EPA RMP guideline of 25% (EPA RMP Handbook 1991). Due to the nature of the data obtained, and that 85% of the measurements were obtained through the two EPA RMP chamber sites, determinations can not be made on why there is a slight under-reporting of the devices, or why there were devices more than 40% off.

Stability

Overall the tables indicate that the electrets are stable. In general they appear to lose about a half volt per week whether it is in the field or in the analysis lab. In fact, only 4.2% of all green electrets and 6.3% of all blue electrets changed more than 1 volt per week. It is also encouraging to see that most of the 90th percentile average voltage change per week data is below the 1 volt per week criteria. This and the median values show that the electrets are skewed toward lower voltage losses. Tables 7 and 8 appear to show that electrets lose less voltage at lower voltage levels.

Differences in voltage change caused by manufacturing variations, shipping of electrets, and storage media can be tested by statistical means. Assuming that voltage losses from electrets are normally distributed, Z-values can be computed and used for hypothesis testing at the 95% confidence interval. Thus, tables 4, 5 and 6 can be used to show that green electrets have significantly less voltage change than blue electrets. This can be done by identifying the null hypothesis as the average change of green electrets minus the average change of blue electrets is equal to or greater than zero. In other words, green electrets change more than blue electrets. The test statistic used was:

$$Z = [(x_{1avg}-x_{2avg})-0]/[(s_1{}^2/n_1)+(s_2{}^2/n_2)]^{0.5}$$

where: x_{1avg} = average volt loss per week of green electrets
s_1 = standard deviation of green electrets
n_1 = number of green electrets
subscripts of 2 are for the blue electrets

At a 95% confidence interval, a Z-value of -1.96, one would reject the null hypothesis when the test statistic produces higher values. The Z-values calculated from tables 4 through 6 were -1.8, -6.1, and -4.0 respectively (p-values of 0.037, less than 0.0001, and less than 0.0001). Tables 5 and 6 show there is strong evidence to reject the null hypothesis. Table 4 however, could have rejected the null hypothesis at a confidence interval of 90%.

The second hypothesis tested was whether electrets in S-chambers returned from the field unused, where they were all shipped via overnight express airmail service, had a greater voltage change than those kept in S-chambers at the analysis laboratory. In this case, it is necessary to only compare green electrets with green electrets and blue with blue, because of the conclusion reached above. Thus, the null hypothesis would be that the average change of green traveling electrets in shells minus the average change of green electrets in shells at the lab is greater than zero. Using the same test statistic as above, the Z-value calculated for the green electrets was -7.3 (a p-value of less than 0.0001) leading to rejection of the null hypothesis. For blue electrets, the Z-value was -8.1 (less than 0.0001). for the green and blue electrets from tables 5 and 6 were both less than 0.001. The same conclusion can also be drawn when comparing data from electrets in caps and traveling electrets in shells.

Finally, hypothesis testing can be used to show that blue electrets in keeper caps (Table 4) are more stable than blue electrets in S-chambers at the lab (Table 6). The null hypothesis would be that the average change of the blue electrets in caps minus the average change of blue electrets in S-chambers is greater than or equal to zero. The null hypothesis is rejected with a Z-value of -3.5 (p-value of 0.0002). A possible reason for this rejection however, is the purchase of new S-chambers that were primarily used with the SJ electrets. To confirm this suspicion, hypothesis testing was performed on the SF and SJ series data. The resulting Z-values were 0.84 and -3.7 respectively (p-values of 0.20 and less than 0.002), indicating that blue electrets in older S-chambers are more stable than blue electrets in newer S-chambers. For green electrets, the null hypothesis cannot be rejected due to a Z-value of -0.43 (p-value of 0.33).

CONCLUSIONS

Rad Elec electrets in S-chambers readily meet EPA's suggested percent coefficient of variation of less than or equal to 10% at radon levels at or above 4.0 pCi/L and can even be held to a more stringent guideline. E-PERMs also appear to be accurate with a slight tendency to under-report levels. With regard to stability, several conclusions can be drawn. First, green electrets are more stable than blue electrets. Second, blue electrets in caps appear to be more stable than those in S-chambers. Finally, there is no significant difference between electrets stored at the lab and electrets shipped via express air mail.

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